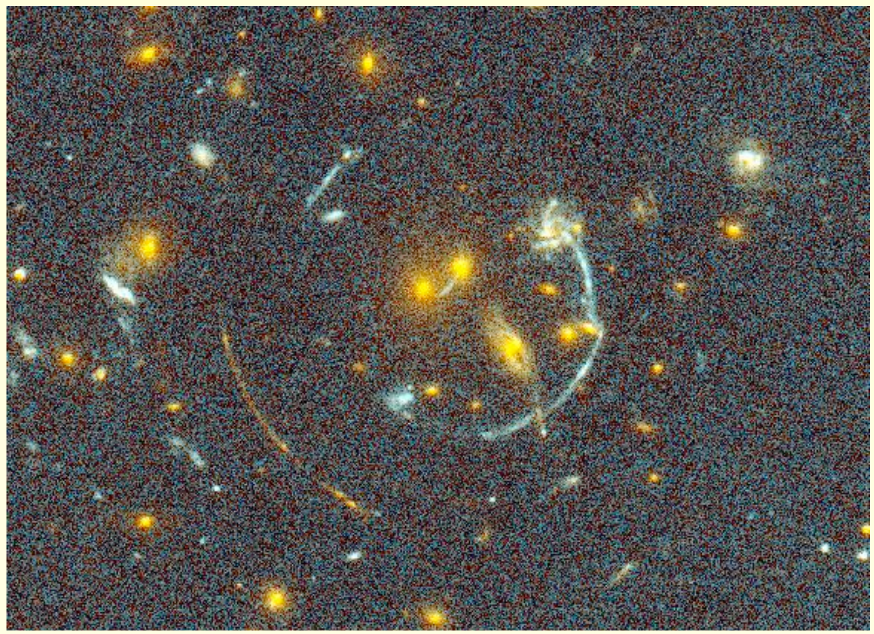
Study of galaxy clusters

…using weak lensing



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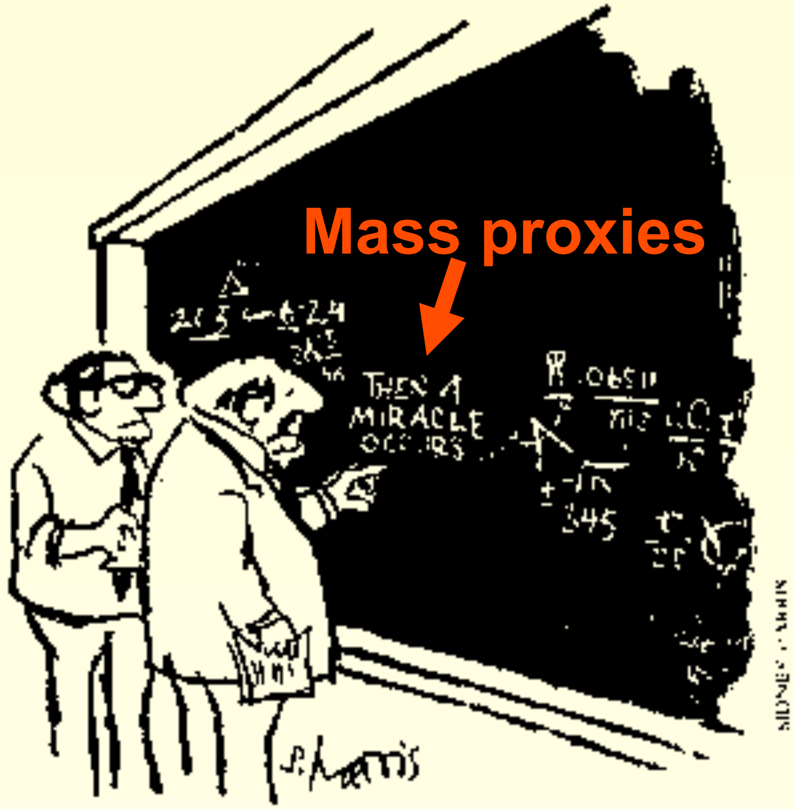
L'Institut canadien de recherches avancées

Masses are important

Cluster survey →



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

→ Cosmology?

But how to weigh clusters…

… when they are *not*:

- *Simple*
- *Relaxed*
- *Spherical*

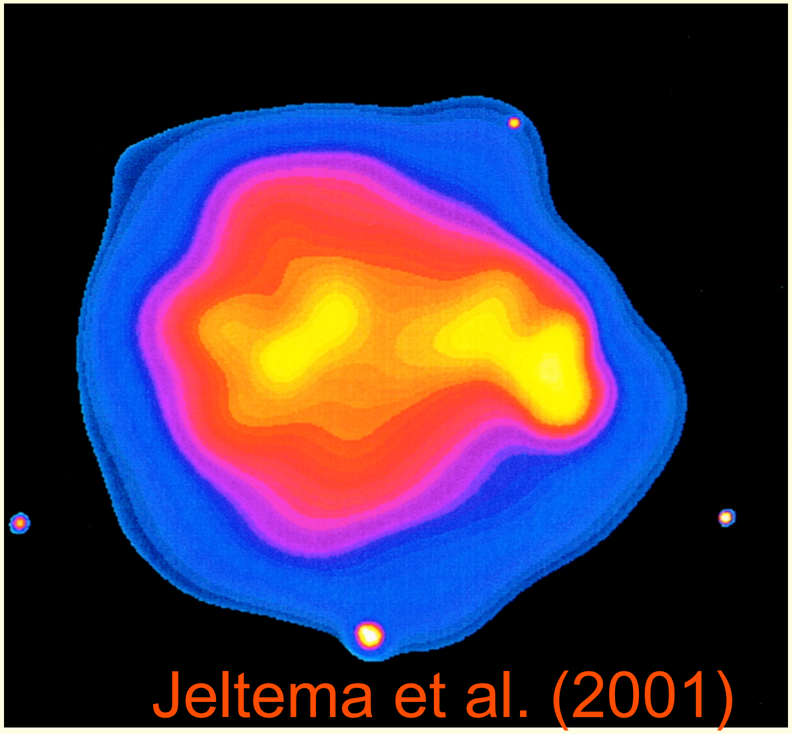
?

Clusters have a complicated history of multiple mergers resulting in complicated geometries with a lot of substructure.

Clusters become particularly messy at high redshift. For attempts to measure the equation of state of the dark energy this is a key redshift range…

How to measure the mass of …

MS1054-03 (z=0.83)

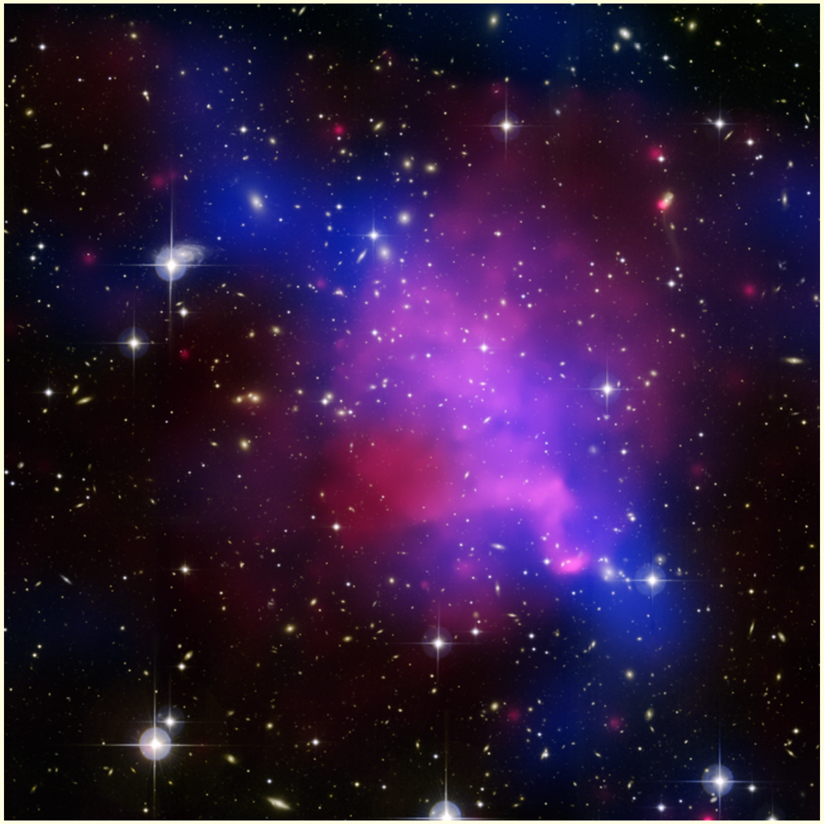


Jeltema et al. (2001)

The light distribution consists of multiple clumps

How to measure the mass of …

Abell 520 (z=0.20)



Dark matter/X-ray peak, without galaxies?! (Mahdavi et al. 2007)

How to measure the mass of …

"Bullet Cluster"

Clowe et al. (2006)

Do we care?

Can we ignore these clusters because they are extreme examples?

It depends on the application…

The extreme systems do need to be included in cluster abundance studies. But for studies of the evolution of gas fractions as a function of redshift they may be ignored.

However, every cluster at some level will be more complex than anticipated…

Comparison to "real life"

We can simulate the formation of dark matter structures fairly well using large N-body calculations (only gravity)

Key question: how to relate the observables to the results of these simulations?

- Mass estimates depend on geometry/dynamical state
- Predictions depend on (complex) gas physics

Solution: simulate clusters!?

Much progress has been made in improving the realism of simulations of cluster formation.

The interplay between better/more observations and larger /more detailed simulations will improve matters significantly in the coming years.

The key questions:

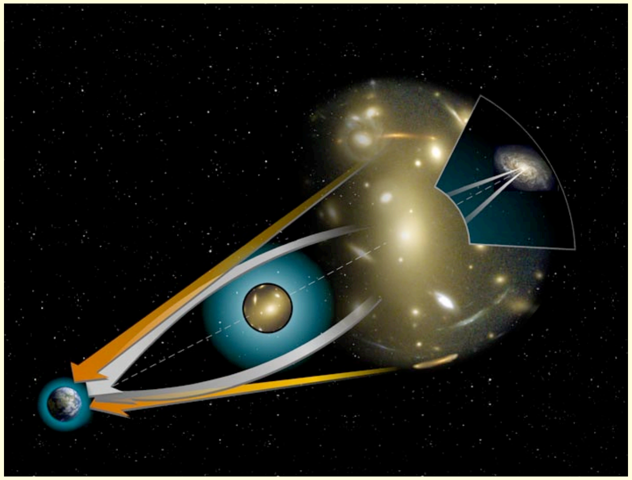
- How can we compare the observations to cosmological predictions?
- Does our incomplete understanding bias the results?

Gravitational lensing

or … *Nature's own weighing scales*

Zwicky (1937): "… The gravitational fields of a number of "foreground" nebulae may therefore be expected to deflect light coming to us from certain background nebulae. The observations of such gravitational lens effects promises to furnish us with the simplest and most accurate determination of nebular masses. *No thorough search for these effects has as yet been undertaken*."

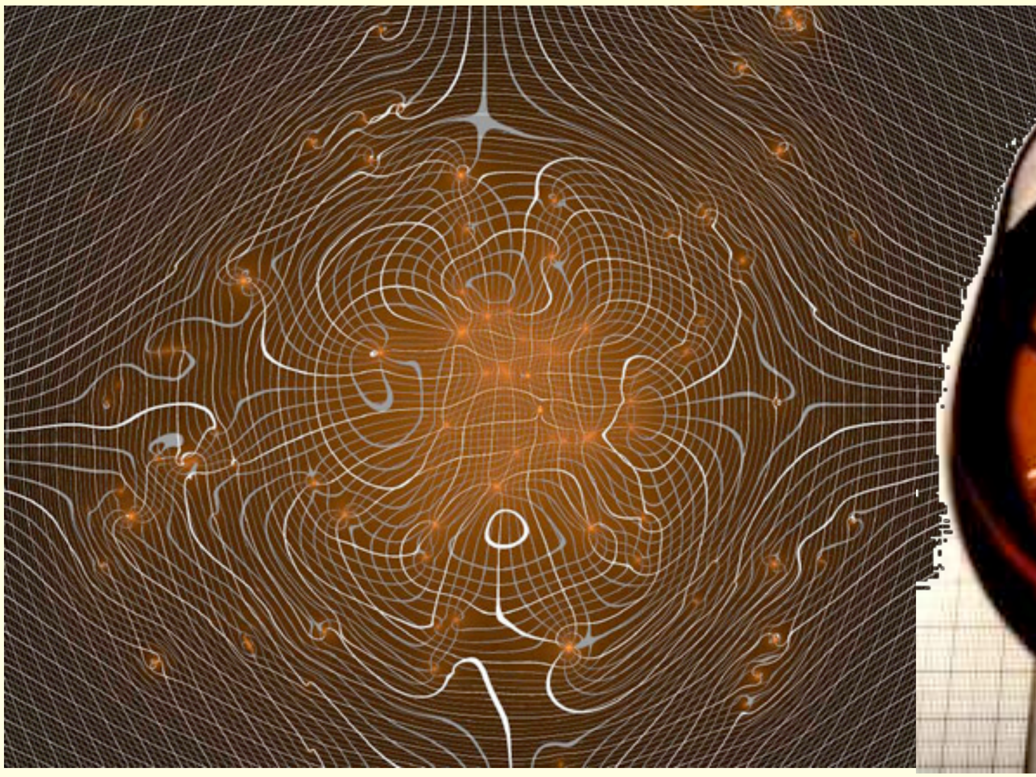
Gravitational lensing

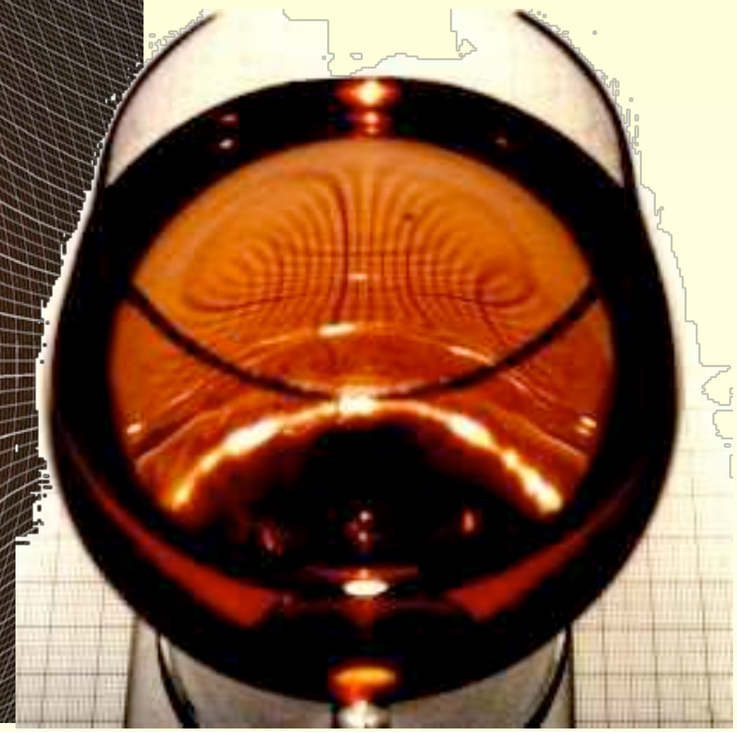


Observations of the (weak) gravitational lensing signal provide a powerful way to study the dark matter distribution in the universe.

- ❑ It does not require assumptions about the dynamical state of the system under investigation.
- ❑ It can probe the dark matter on scales where other methods fail, as it does not require visible tracers of the gravitational potential.

Gravitational lensing





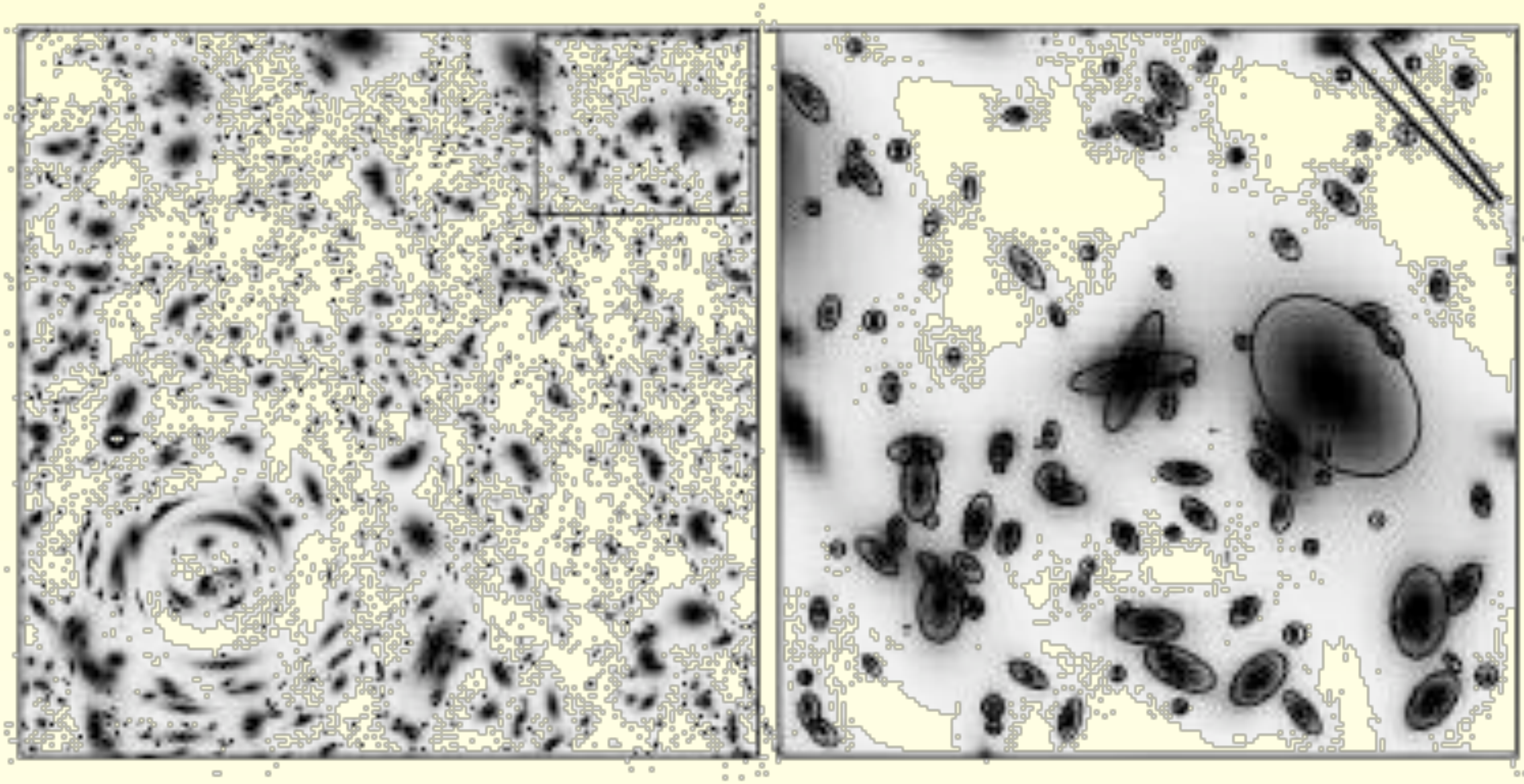
The cluster mass distribution causes a distortion in the shapes of background galaxies. The leads to spectacular lensing examples.

Gravitational lensing

Galaxy Cluster Abell 2218 **HST** • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

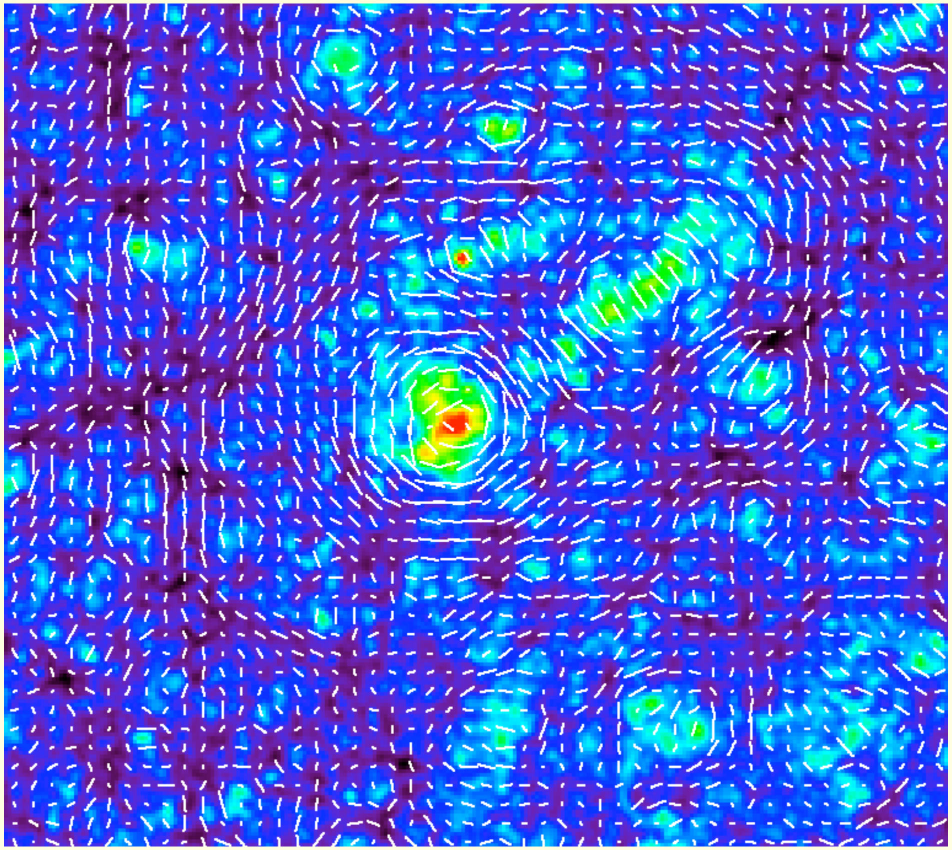
What is weak lensing?



A measurement of the ellipticity of a galaxy provides an unbiased but noisy measurement of the gravitational lensing shear

We can see dark matter!

Courtesy B. Jain



In the absence of noise we would be able to map the matter distribution in the universe (even “dark” clusters).

What do we measure?

Underlying assumption: the galaxy position angles are uncorrelated in the absence of lensing

1. Measure the galaxy shapes from the images
2. Correct for observational distortions
3. Select a sample of background galaxies

↓

Lensing signal

The conversion of the lensing signal into a mass requires knowledge of the source redshift distribution

Dealing with systematics: the PSF

Weak lensing is rather unique in the sense that we can study systematics very well.

Several diagnostic tools can be used. However, knowing systematics are present doesn't mean we know how to deal with them…

But we can readily simulate weak lensing surveys. The Shear TEsting Programme (STEP) is aiming to improve our techniques this way.

Dealing with systematics: tests

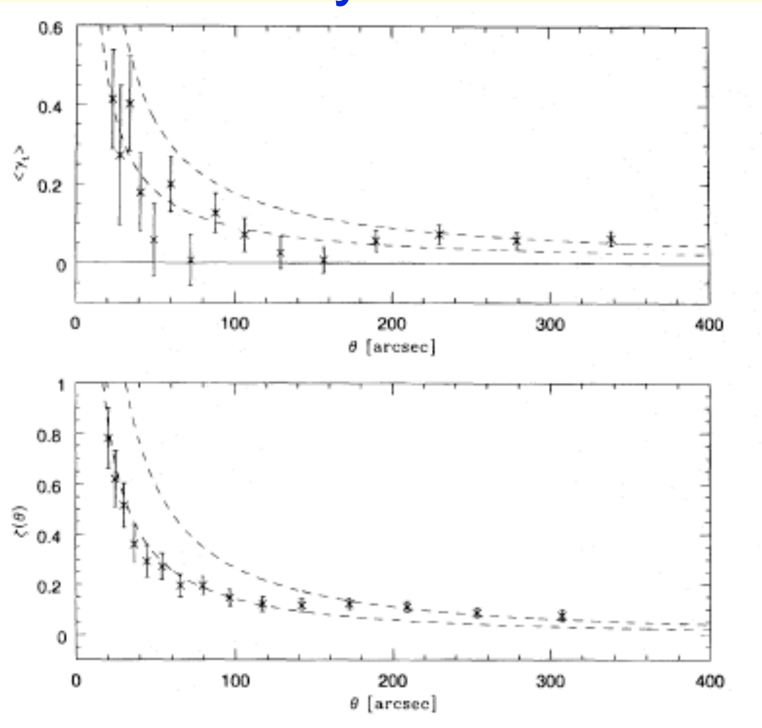
It is relatively easy to create simulated data to test the measurement techniques.

The Shear TEsting Programme is an international collaboration to provide a means to benchmark the various methods.

So far two papers have been published (Heymans et al., 2006 and Massey et al., 2007). These results provide a snapshot of the current accuracy that can be reached (~1-2%).

The early days…

A handful of clusters were studied in the ’90s using cameras with relatively small fields of view.

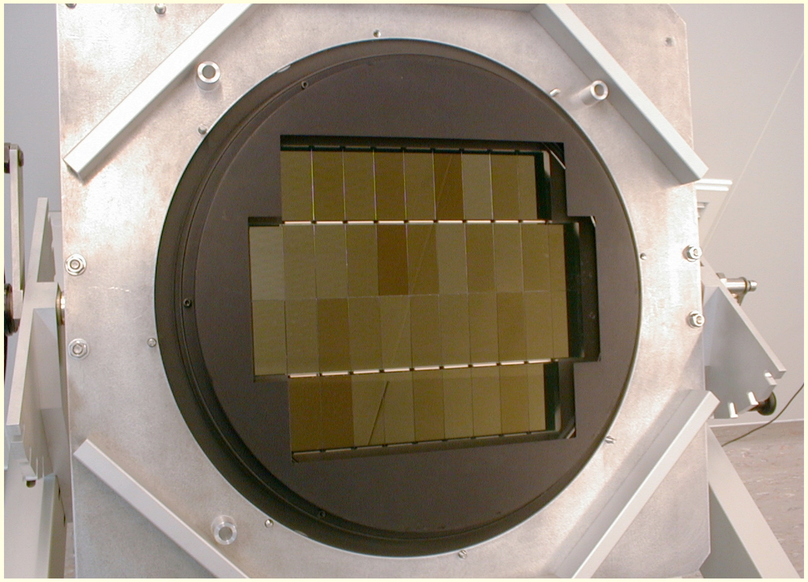


Abell 2218: Squires et al. (1996)

A new millenium…

In 2000 the first cosmic shear detections were published, and cluster weak lensing was no longer "fashionable" (if it ever was…)

But the wide field imagers developed for cosmic shear are great for cluster work as well, as we can image large samples of clusters out to large radii!



Large(r) cluster samples

A sample of clusters with accurate weak lensing masses is important for the success of cluster abundance studies.

Requires large range in mass/redshift

Only a relatively small number of clusters have accurate weak lensing masses (but this is changing!)

Cluster mass profiles: comparison with other tracers

Learn about cluster physics

Canadian Cluster Comparison Project

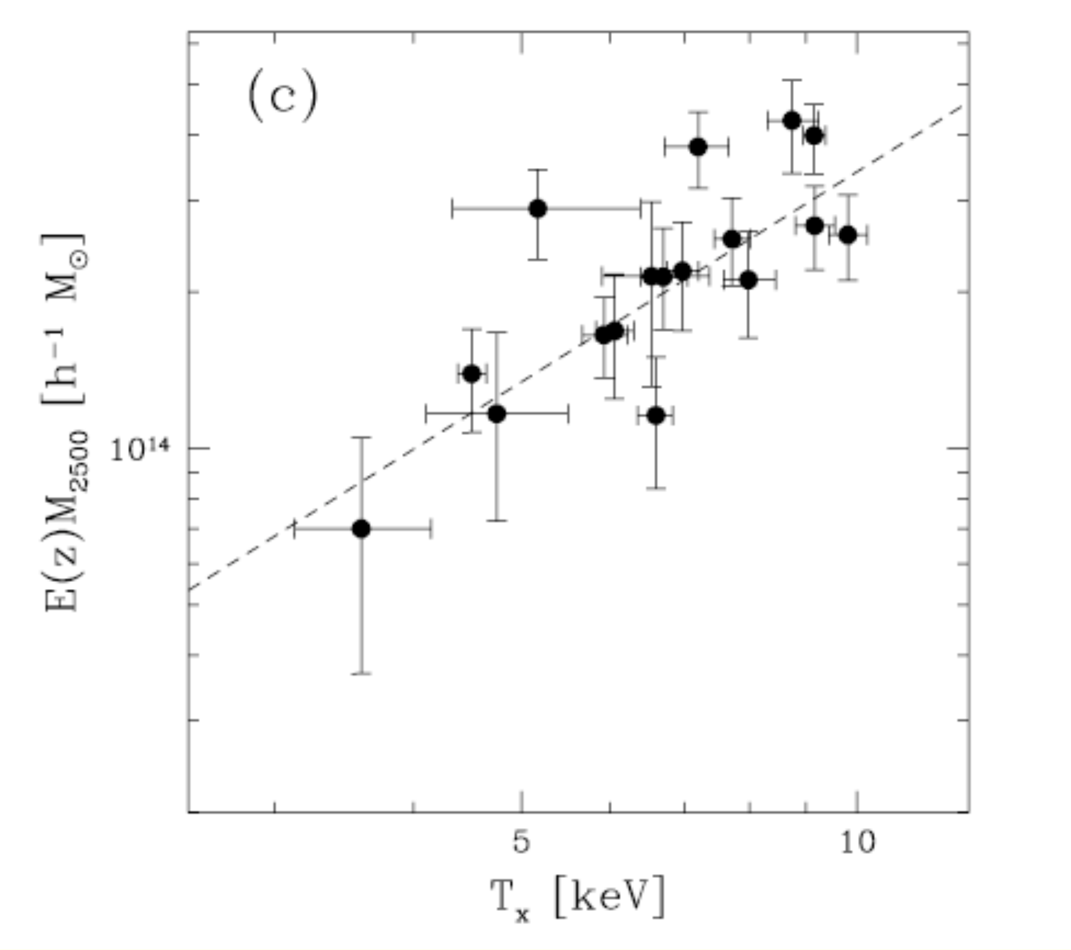
CCCP: “good for the masses”

- Sample of 20 well known clusters imaged with CFH12k.
- Obtained CFHT Megacam data for 30 more clusters
  - ASCA/Chandra X-ray temperatures
  - Dynamical data
  - SZ measurement (e.g., CBI)
- CFHTLS will also provide a large sample (~1000).

Goals:

- Calibration for cluster abundance studies
- Study properties of the ICM

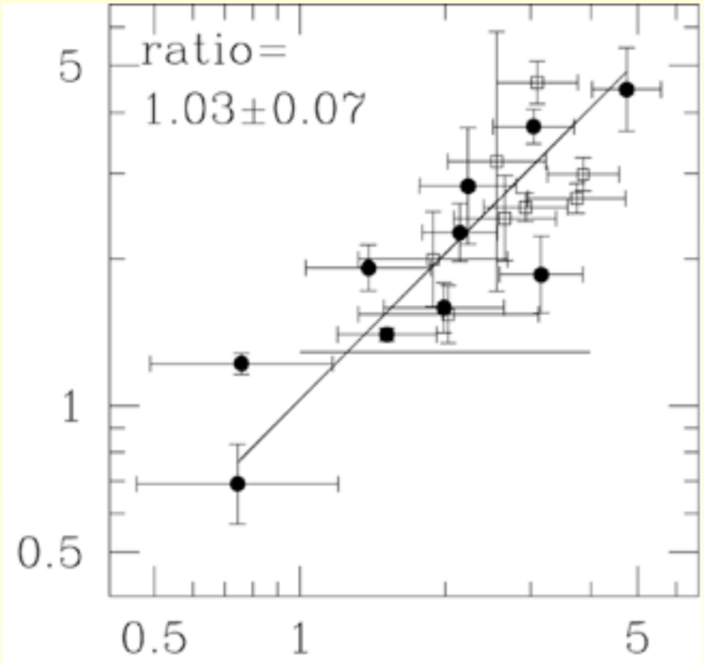
Comparison with X-ray data

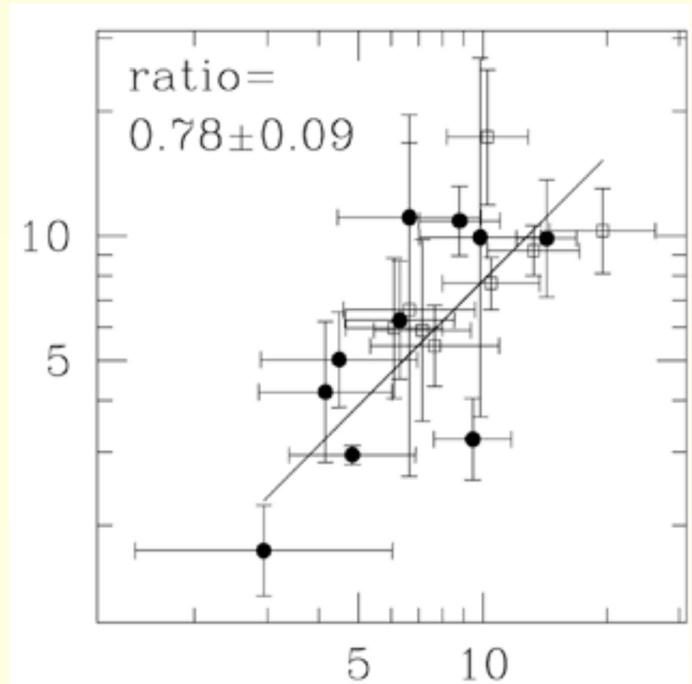


Hoekstra (2007)

A more detailed comparison…

X-ray mass



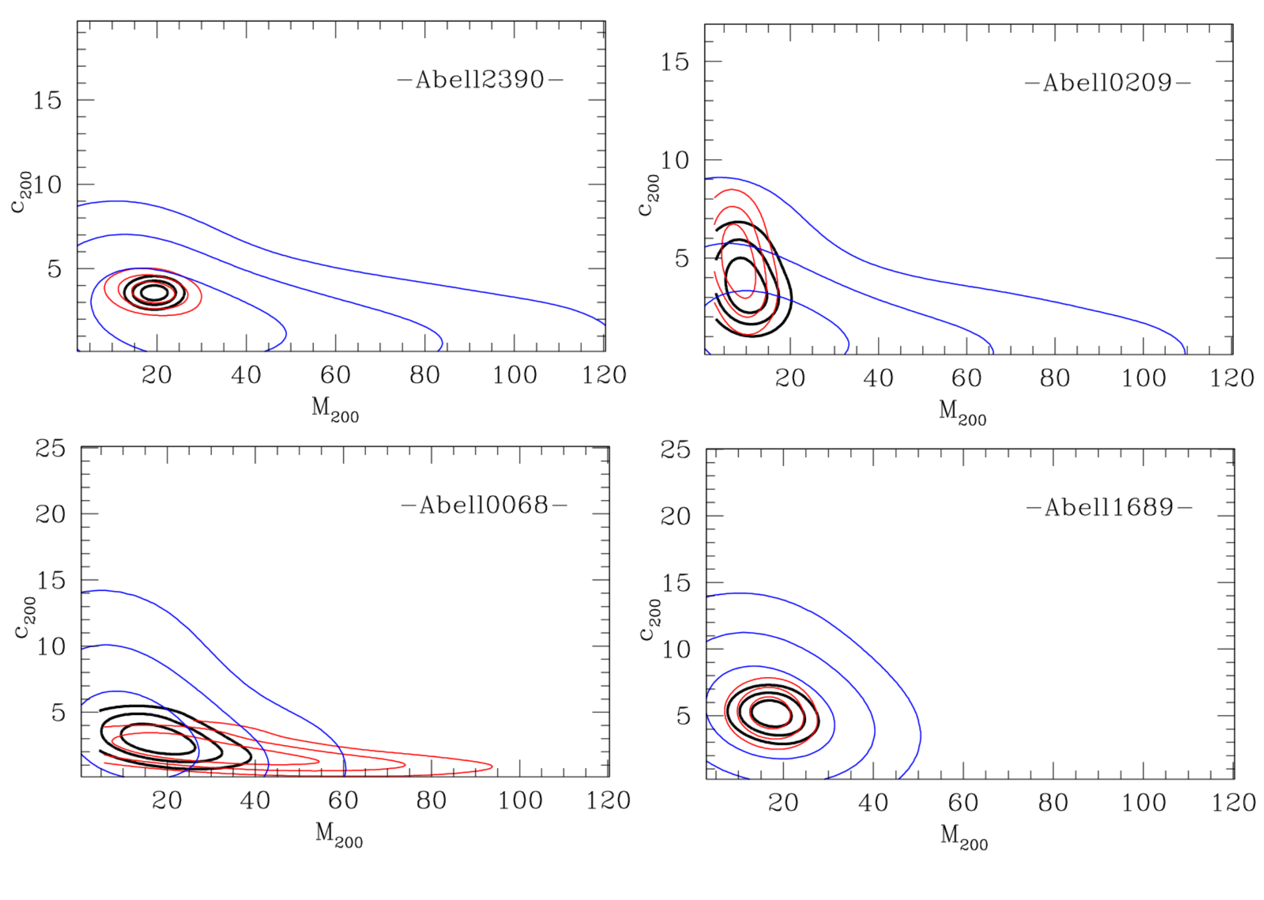


lensing mass

At large radii clusters are not in hydrostatic equilibrium

Mahdavi et al. (2008)

A more detailed comparison…

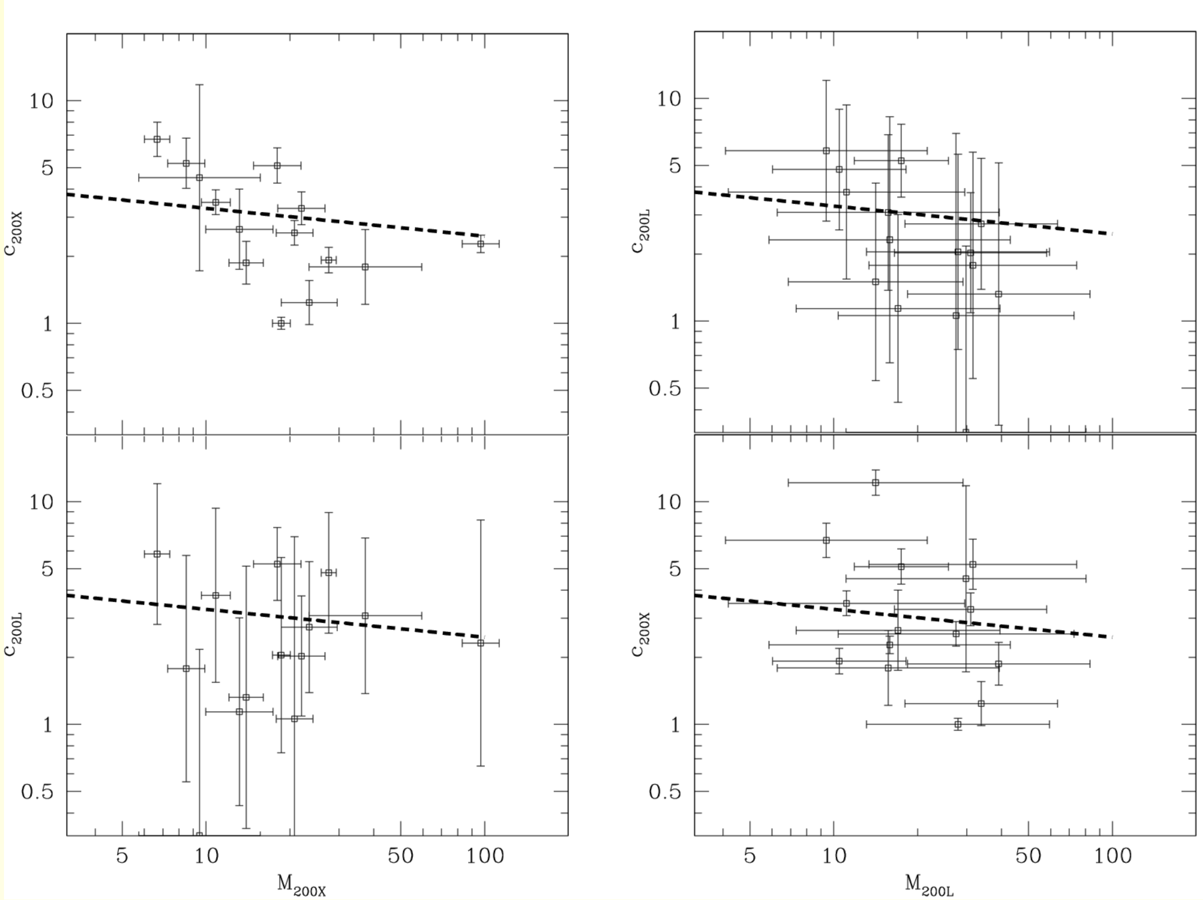


X-ray+lensing modeling Mahdavi et al. (in prep)

A more detailed comparison…

correlated

uncorrelated



Mahdavi et al. (in prep)

Stacking clusters

For lower masses, one can still learn about the cluster properties by stacking the signal of many systems. This is for instance done for galaxy groups (Hoekstra et al. 2001; Parker et al. 2006).

Similarly, although the SDSS imaging is not deep enough to study the masses of individual clusters, the signals of similar systems can be combined.

For instance this allows studies of the cluster mass profile out to large radii.

Cluster density profiles

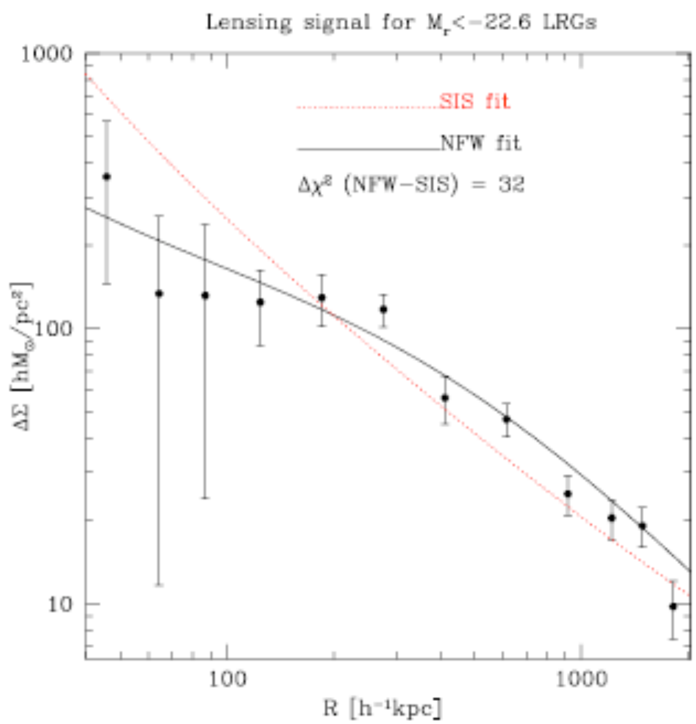


Figure 10. Lensing signal for the $M_r < -22.6$ lens sample averaged over source sample.

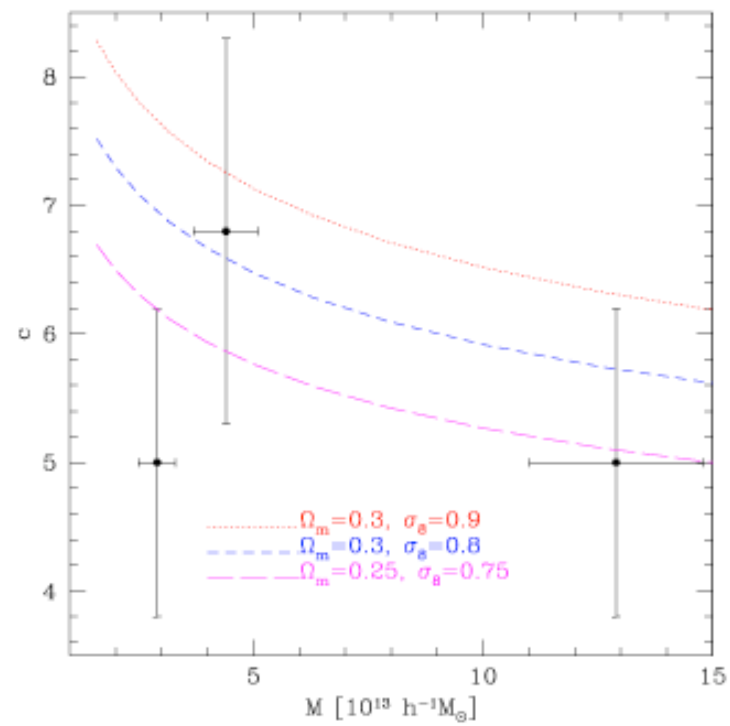
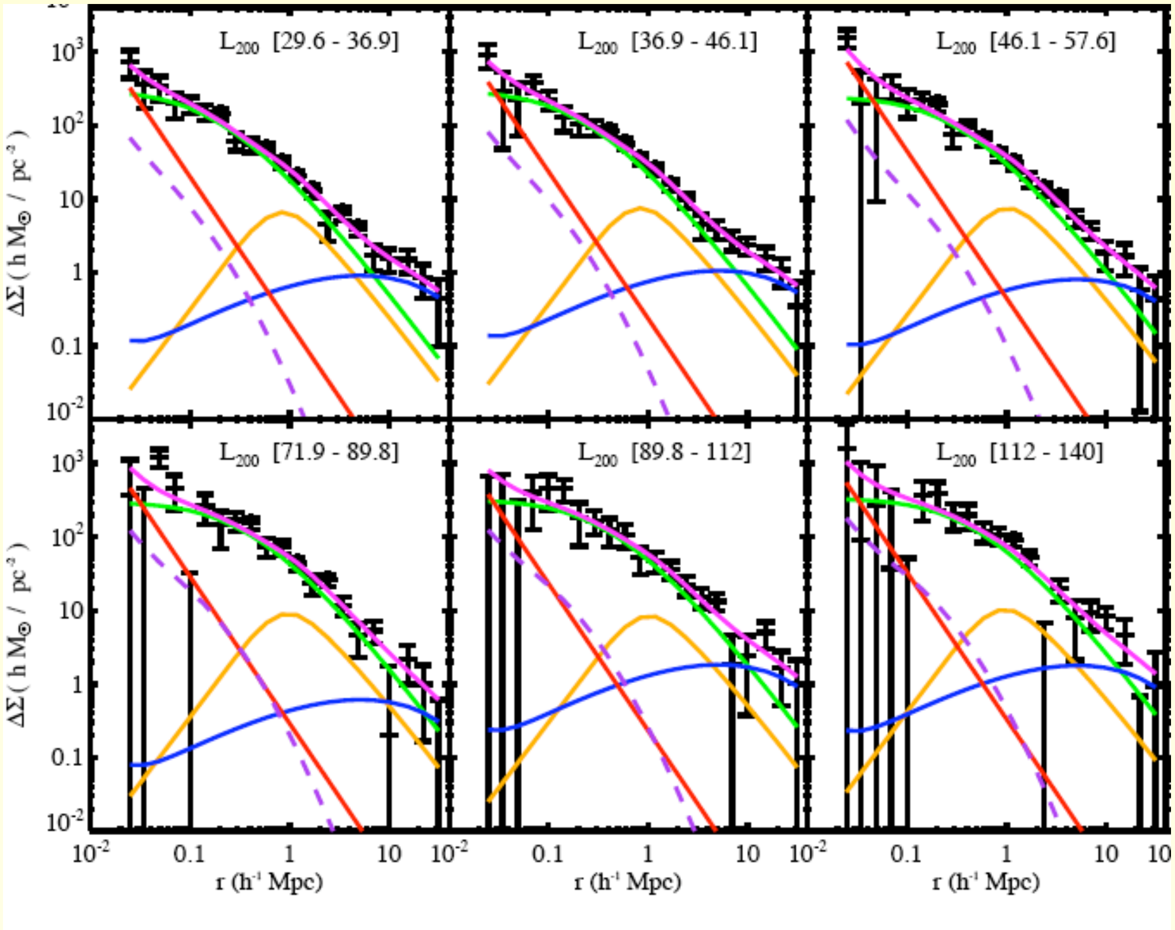


Figure 11. Measured NFW concentrations with statistical and systematic errors added in quadratures, shown as a function of best-fit NFW mass. The lines shown on the plot are predictions for several different cosmologies.

Mandelbaum et al. (2007)

Cluster density profiles



Johnstone et al. (2007)

Limitations of weak lensing

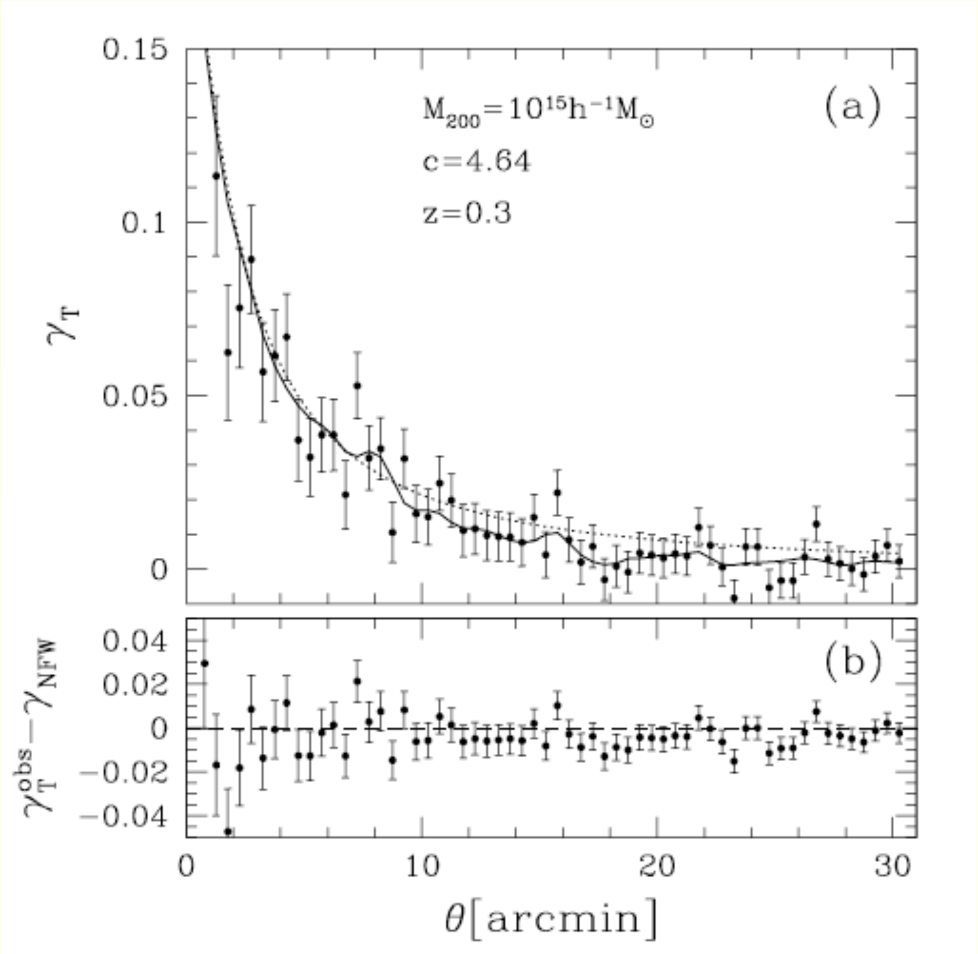
- Weak lensing gives the projected mass distribution
- The weak lensing signal depends on all matter along the line of sight
- The interpretation of the signal requires good knowledge of the source redshifts

Uncorrelated large scale structure is an additional source of noise

↓

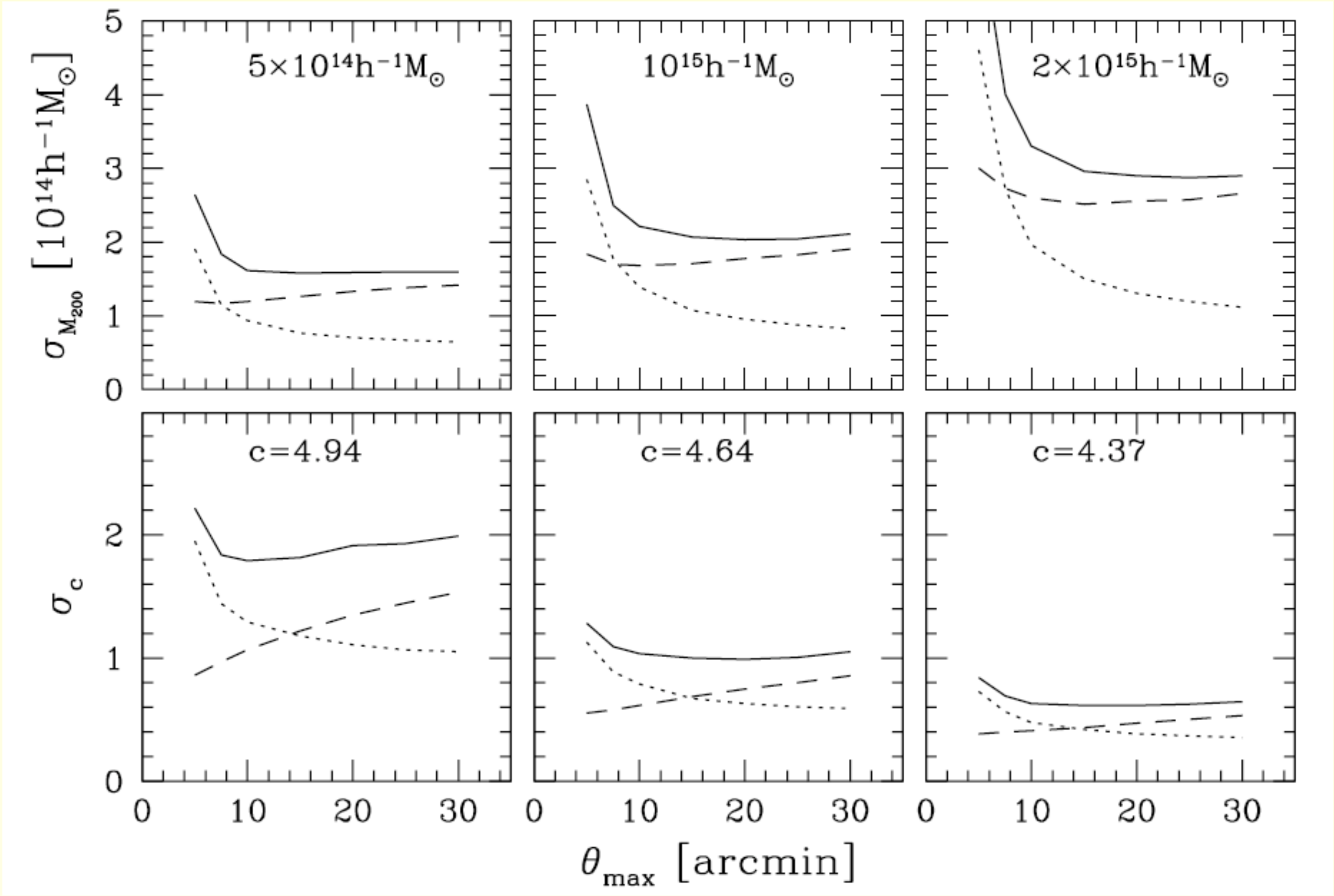
Limits the accuracy with which masses can be determined

Effects of distant structures



Hoekstra (2003)

Effects of distant structures



Hoekstra (2003)

Effects of projections

White et al. (2002)

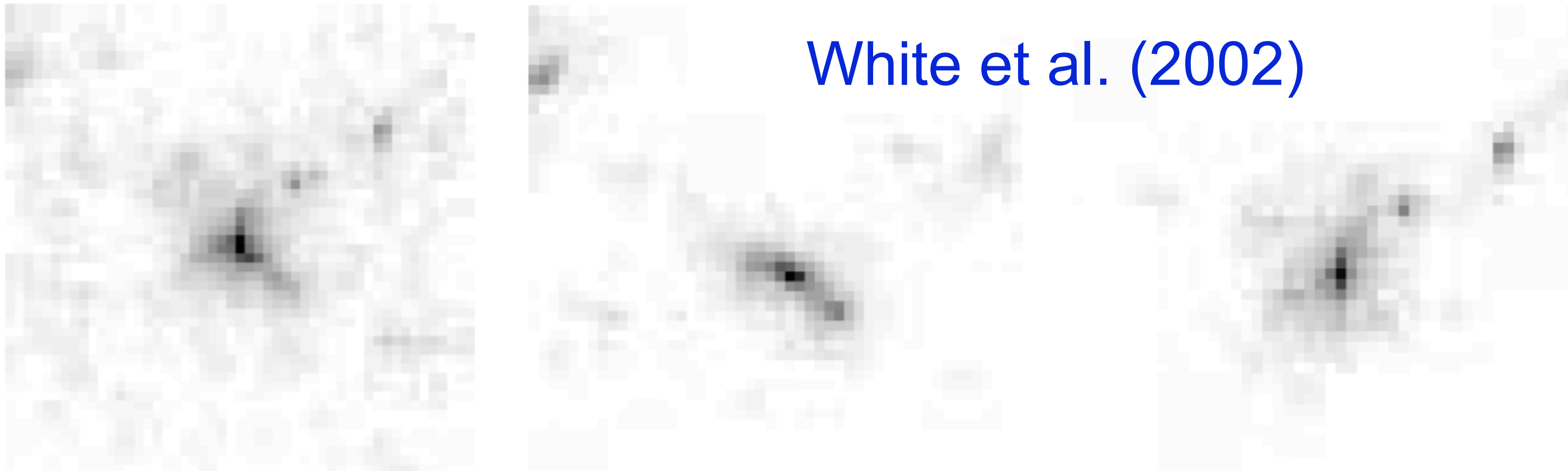
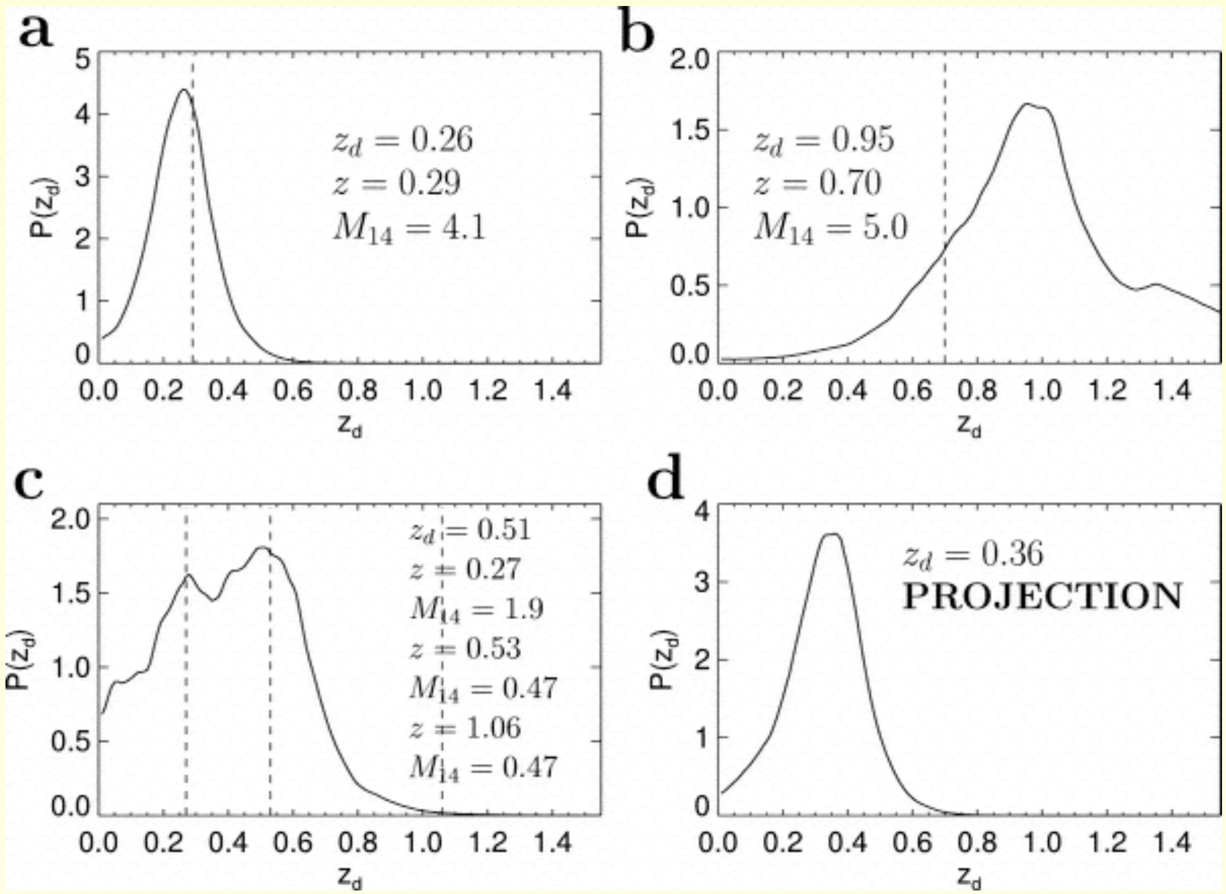


FIG. 5.—Zoom-in of one of our convergence maps showing two clusters that lie almost on top of each other in projection. *Left*: Full κ map. *Middle*: Portion coming from the 100 h^{-1} Mpc slice at low redshift. *Right*: Portion coming from the 100 h^{-1} Mpc slice at higher redshift. The regions shown are $0\overset{\circ}{.}3$ on a side.

Projections are also important when studying peaks in large scale weak lensing maps.

Effects of projections



Hennawi & Spergel (2005)

Effects of projections

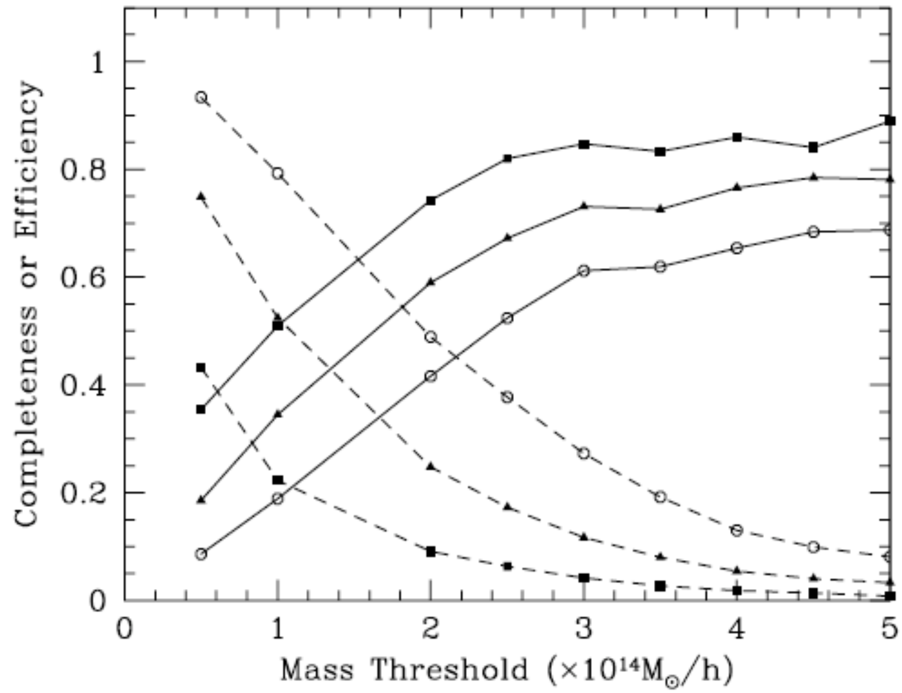


FIG. 10.—Efficiency and completeness as a function of mass for maps with a $\simeq 3'$ filtering scale. Solid lines show completeness and dashed lines efficiency. Filled squares are for $S > 3$, triangles for $S > 4$, and open circles for $S > 5$. The statistics at the high-mass end become very poor.

White et al. (2002)

Summary & Conclusions

- Weak gravitational is the weighing scale of choice, but does have limitations!

- Key ingredient in cluster abundance studies

- Comparison with other probes will provide new insights in cluster physics/formation

Much progress expected in the coming years

The future is bright!

Much progress can be expected in the coming years using larger surveys and (photometric) redshift information.

- more SDSS results
- RCS2 (1000 square degrees in g,r,z)
- CFHT Legacy Survey (170 square degrees, 5 filters)
- follow-up of SZ-surveys (APEX, SPT)
- Targeted weak lensing analyses